TEST OF PROCESS TURBOCOMPRESSORS WITHOUT CFC GASES

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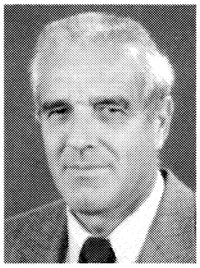

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ABSTRACT

Increasing restrictions from environmental protection laws will necessitate at least partial substitution of chlorofluorocarbon (CFC) gases still in use today for performance tests of turbocompressors in closed loops. The International Compressed Air and Allied Machinery Committee (ICAAMC), therefore, formed a working group which investigated substitution possibilities for the most commonly used CFC Freon R22 (R12). The working group has come to the conclusion that R134a can be used as a substitute test gas in full compliance with standard test procedures. The theoretical results have been confirmed by a performance test with R134a and parallel measurements with R22. The working group recommends putting a ban on the use of CFC gases which contain chlorine. The main aspects which justify this recommendation are discussed.

PURPOSE OF THE THERMODYNAMIC PERFORMANCE TEST

The rules for thermodynamic performance tests are formulated in established codes like ASME PTC 10 [1] or VDI 2045.

The object of the thermodynamic performance test is to operate the compressor under conditions that allow a reliable prediction of the performance at site conditions. If the test gas is the specified gas, this prediction is straightforward. If not, the test setup must be such that the test data can be converted to specified operating conditions. This will be assured if the matching of the individual stages is identical at test and specified operation, and this in turn implies identical dimensional suction volume flow coefficient of the stages. This can be achieved by operating the compressor in both modes at identical circumferential Mach numbers Mu2.

In many instances, the thermodynamic performance test cannot be carried out with the gas that the unit is designed for; in such cases, a proper substitute gas must be selected which fulfills the stated requirements.

If the difference in k-values of both gases is within some ± 15 percent normal, similarity to operation can be obtained by adjusting the mechanical speed. If, however, the spread in k-values is higher, the resulting temperature rise across the stages causes density deviations that cannot be compensated by mechanical speed and the departures from specified design parameters will be outside the allowable limits as stipulated in the codes.

In Table 3 of the ASME PTC 10 POWER TEST (Table 1) the tolerance band of the test performance parameters is stated with respect to volume ratio, capacity-speed ratio, Mach number, and Reynolds number. This code fixes also the limits of the departure of the test gas properties from the perfect gas laws; data lying within the tolerances can be converted via perfect gas laws (Class II), otherwise data must be converted with real gas equations (Class III). Furthermore, a substitute gas for shop tests must be:

- nonflammable
- nontoxic
- thermally stable and should have a higher molecular weight than the specified gas, to assure a mechanical test speed lower than the design speed.

Table 1. Allowable Departures from Specified Design Parameters for CLASS II and III Performance Tests.

Variable	*Symbol*	*Range of Test Values Limits — % of Design Value* Min	Max
Volume ratio	q/q_d	95	105
Capacity-speed ratio	q/N	96	104
Machine Mach Number	M_m		
0 to 0.8		50	105
Above 0.8		95	105
Machine Reynolds Number where the design value is	R_e		
Below 200,000 Centrifugal		90	105
Above 200,000 Centrifugal		10*	200
Below 100,000 Axial Compressor		90	105
Above 100,000 Axial Compressor		10**	200

*Minimum allowable test Machine Reynolds number is 180,000
**Minimum allowable test Machine Reynolds number is 90,000

For closed loop performance tests of hydrocarbon gas mixtures the k-value should be smaller than approximately 1.2. On isolated occasions, CO_2 (k = 1.3) can be employed, but in most cases the CFC gases Freon R12 or R22 are ideally suited for closed loop testing of compressors designed for hydrocarbon duty, and for decades they have been well established and accepted test gases.

Faced with the ban of these CFC gases, a suitable replacement gas must be selected.

CFC GASES IN USE TODAY ENVIRONMENTAL IMPLICATIONS REPLACEMENT GASES

Due to the environmental threats identified during the last two decades, regulations were established on substances that deplete the ozone layer and are a potential source of global warming; CFC gases are in this class of chemical compound and the use and production of them will soon be banned.

Among others, the most widely known acts are the treaty called "Montreal Protocol" and the Council Regulations (EEC) No. 594/91 [2]. The "Montreal Protocol" signed in 1988 took effect on January 1, 1989, and at a conference in London (June 1990) it was formulated more strictly.

The most important aspects of that ruling are:

- All CFC gases (such as R11 and R22) and Halones (R13B1) along with carbon tetrachloride and trichloroethane are subject to that ruling.
- The use and production of CFC and Halones must be phased out as shown later.

The United States set even stricter requirements—R12 will be phased out by December 1995. This especially calls for a substitution of R22 and R12 as closed loop test gases.

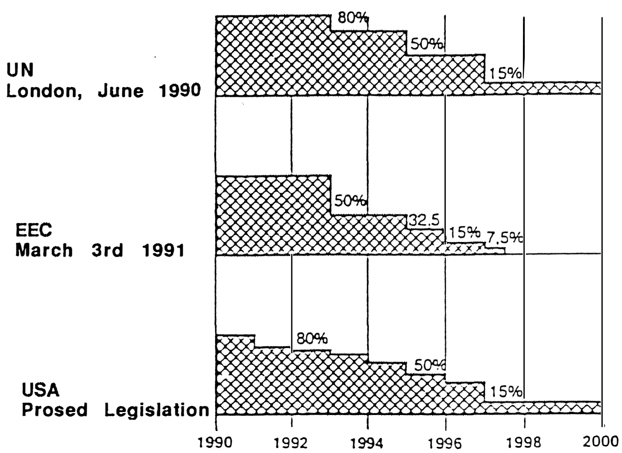

Figure 1. Scenario for Phasing out CFC Gases.

An important set of criteria for the evaluation of a replacement gas is given in Table 2. Considering the replacement gases available to date, R134a very obviously became the top candidate. The chemical structure quickly reveals that chlorine is completely absent; consequently, the ozone depletion potential is zero. The comparison presented in Table 2 also shows a reduction of the global warming potential of about 17 percent if compared to R12. While this is of minor importance, it is worthwhile to note that the stability of R134a is very good and not inferior to R22.

Based on a comprehensive evaluation and on the fact that R134a will be in use for many refrigeration applications, it was decided to further investigate this replacement gas as a possible substitute gas for closed loop testing. Since R134a has emerged as the leading replacement for R12, there has been much interest in the representation of the thermodynamic properties including their accurate measurement. Several sets of equations are in use today, one of the best known being the modified Benedict-Webb-Rubin equation of state with coefficients of the National Institute of Standards and Technology [3]. Data derived from measurements are very much in accordance with the calculations (Appendix 1).

Table 2. Criteria for the Selection of Replacement Gases.

Substance	*Chemical Structure*	*Ozone Depletion Potential*	*Global Warming Potential*	*Chemical Stability (Years)*
CFC in use (Selection)				
R12/FCKW12	CCL2F2	0.92 - 1.0	2.8 - 3.4	120
R22/H-FCKW22	CHCLF2	0.042 - 0.057	0.34 - 0.37	15.3
Potential Replacement Gases (Selection)				
R134a/H-FKW 134a	CH2F-CF3	0	0.25 - 0.29	15.1
R152a/H-FKW 152a	CH3-CHF2	0	0.026 - 0.033	1.7
For Comparison				
Carbon Dioxyde	CO2	0	0.0003	

R134A—COMPARATIVE CALCULATIONS

The behavior of R134a was first investigated using the basic design data of a side stream propane compressor, as treated in the VDI code 2045. The design data of this compressor are listed in Table 3.

Table 3. Design Data of the Propane Compressor.

Mass flow	Kg/s	13.95
Suction pressure	bar	1.373
Suction temperature	°C	-32.3
Gas constant	J/gk k	188.6
Side stream flow	Kg/s	10.13
Side stream pressure	bar	4.26
Side stream temperature	°C	-3
Disch. pressure	bar	10.34

Steps of This Analysis

- For a closer assessment, the overall behavior of the two stage groups was analyzed as outlined in the codes, and the matching of the individual stages at the various gas duties. A thermodynamical layout based upon the design data defines the physical dimensions of the stages. The detailed stage data are given in Table 4.
- The necessary mechanical test speeds were computed as outlined in the ASME PTC 10 code. This information and pertinent thermodynamical data for test and design conditions are shown in Tables 5 and 6.
- Taking the thus computed mechanical test speeds and the defined geometry of the stages the overall performance curves could be calculated.

The relevant thermodynamical data of design and test conditions are presented in Table 7.

The characteristics polytropic head *vs* suction volume flow are shown in Figures 2 and 3. For better comparison, both the volume

Table 4. Stage Data of the 5-Stage Propane Compressor.

Stage	*Imp. tip. dia. mm*	*Tip speed m/s*	*Circumf. Mach No. Mu2*	*Flow Coeff.*	*Inlet Pr. bar*	*Inlet Temp °K*
1	560	225	1.01	0.0642	1.373	237.7
2	560	225	0.98	0.0396	2.463	264.5
3	500	200	0.88	0.0551	4.266	280.7
4	500	200	0.87	0.0376	6.453	299.1
5	500	200	0.86	0.0249	10.003	319.3
Discharge					15.1	339.7

Table 5. Determination of Test Conditions according to ASME PTC 10 Power Test Code LP-Section.

Gas		*Spec. Gas Propane*	*Test Gas R22*	*Test Gas R134a*
Molecular Weight	Kg/Mol	44.097	86.48	102.03
Mechanical Speed	RPM	7649	6486.6	5650
Inlet Pressure	Bar	1.373	0.8	0.8
Inlet Temperature	°K	240.84	313.15	313.15
Pressure Ratio	—	3.107	3.125	2.914
Compr. Factor	—	0.953	0.991	0.986
Outlet Pressure	Bar	4.266	2.5	2.331
Outlet Temperature	°K	288.12	377.48	351.7
Inlet Volume Flow	M3/S	4.399	3.73	3.249
Inlet Mass Flow	Kg/s	13.95	9.998	10.33
Kin.Visc.First Stage *E+5	—	0.2231	0.4976	0.394
Ratio of k-Values	—	1.093	1.093	1.094
K MAX/K MIN	—	1.054	1.02	1.015
Compr. Functions -X Max**)	—	0.095	0.094	0.105
X Actual In	—	-0.219	0.035	0.061
X Actual Ol	—	0.083	0.061	0.096
X Min**)	—	-0.099	-0.098	-0.109
-Y Max**)	—	1.021	1.021	1.023
Y actual In	—	1.008	1.014	1.037
Y Actual Ol	—	1.095	1.021	1.05
Y Min**)	—	0.977	0.978	0.976
Mach Number	—	1.011	1.02	0.998
Reynolds Number	—	3126348	1188671	1308336
Gas Power	KW	906.3	446.3	350.5
Class of Test			III	III

Variable	Range of Test Values Min.	Max	Test/Specified	
Volume Ratio	0.95	1.05	0.969	0.973
Capacity-Speed Ratio	0.96	1.04	1	1
Mach Number Ratio	0.95	1.05	1.009	0.987
Reynolds Number Ratio	0.1	2	0.38	0.418

**) CLASS II Test Limit

Table 6. Determination of Test Conditions according to ASME PTC 10 Power Test Code HP-Section.

Gas		*Spec. Gas Propane*	*Test Gas R22*	*Test Gas R134a*
Molecular Weight	Kg/Mol	44.097	86.48	102.03
Mechanical Speed	RPM	7649	6486.6	5650
Inlet Pressure	Bar	4.267	2.4	2.4
Inlet Temperature	°K	280.75	313.15	313.15
Pressure Ratio	—	3.539	3.818	3.666
Compr. Factor	—	0.91	0.969	0.957
Outlet Pressure	Bar	15.1	9.126	8.8
Outlet Temperature	°K	339.74	392.7	363.2
Inlet Volume Flow	M3/S	2.717	2.304	2.007
Inlet Mass Flow	Kg/s	24	18.949	19.718
Kin.Visc.First Stage *E+5	—	0.0929	0.1629	0.1281
Ratio of k-Values	—	1.091	1.091	1.091
K MAX/K M	—	1.105	1.032	1.046
Compr. Functions -X Max**)	—	0.079	0.073	0.076
X Actual In	—	0.089	0.111	0.201
X Actual Ol	—	0.125	0.085	0.213
X Min**)	—	-0.082	-0.075	-0.079
-Y Max**)	—	1.019	1.017	1.018
Y actual In	—	1.106	1.063	1.057
Y Actual Ol	—	1.271	1.027	1.057
Y Min**)	—	0.98	0.982	0.981
Mach Number	—	0.879	0.924	0.911
Reynolds Number	—	6035859	2919642	3233160
Gas Power	KW	1911	1005	802
Class of Test			III	III

Variable	Range of Test Values Min.	Max	Test/Specified	
Volume Ratio	0.95	1.05	0.95	0.973
Capacity-Speed Ratio	0.96	1.04	1	1
Mach Number Ratio	0.95	1.05	1.05	1.036
Reynolds Number Ratio	0.1	2	0.484	0.536

**) CLASS II Test Limit

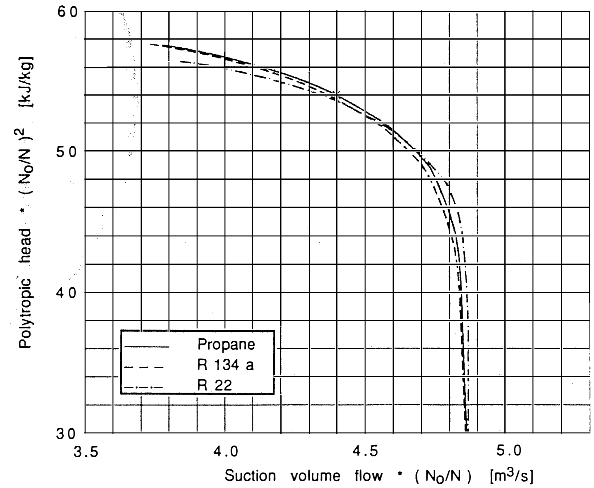

Figure 2. Polytropic Head Vs Suction Volume Flow. LP-stage group.

Table 7. Thermodynamical and Stage Data for Operation with Specified Gas and Test Gases.

Gas		*Propane*	*R22*		*R134a*	
Weightflow	Kg/s	13.95	10.2		10.32	
Inlet 1st stage						
Pressure	bar	1.38	0.8		0.8	
Temperature	°K	237	313		313	
Compr. factor		0.951	0.992		0.986	
Volume flow	m3/s	4.31	3.81		3.25	
Disch. 1st stage						
Pressure	bar	4.26	2.47		2.34	
Temperature	°K	288	378		352	
Compr. factor		0.92	0.984		0.975	
Inlet 2nd stage						
Pressure	bar	4.26	2.47		2.34	
Temperature	°K	280	313		336	
Compr. factor		0.91	0.968		0.97	
Volume flow	m3/s	2.76	2.304		2.03	
Disch. 2nd stage						
Pressure	bar	15.09	10.34		8.08	
Temperature	°K	339	399		385	
Compr. factor		0.813	0.944		0.937	
Gas power	Kw	2828	1583		1120	
Speed	rpm	7650	6487		5645	
Stage data						
Flow coeff.				Dev. %		Dev. %
Stage 1		0.0642	0.0641	-0.2	0.0642	0
2		0.0398	0.0399	0.2	0.0399	0.2
3		0.0551	0.0551	0	0.0549	-0.3
4		0.0376	0.0365	3	0.0374	-0.5
5		0.0249	0.0238	-4.1	0.0252	1.2
Mach. Mach no.						
Stage 1		1.011	1.019	0.8	0.997	-1.4
2		0.978	0.971	0.7	0.965	-1.3
3		0.881	0.925	5	0.872	-1.1
4		0.871	0.984	2.6	0.859	-1.3
5		0.879	0.865	-1.6	0.849	-3.5

flow and the head have been converted to the design mechanical speed: at thermodynamically similar operating conditions, the flow is proportional to the speed and the head proportional to the square of the speed.

Discussion of the Investigation

For the layout of the compressor a design with two stages in the LP-section and three stages in the HP-section has been selected.

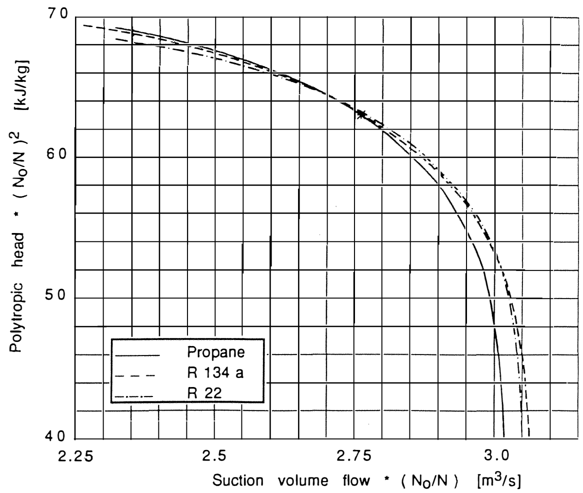

Figure 3. Polytropic Head Vs Suction Volume Flow. HP-stage group.

The thermodynamic behavior satisfies the test requirements of the PTC 10 Code, as proven in Tables 5 and 6. Similar to the R22 data, the compressibility functions indicate that the test data must be converted according to Class III, relying on real gas equations. For R134a test conditions in both sections the ratios of inlet to discharge volume, speed volume ratios, etc., for test to specified operating conditions are very similar to the computed deviations for an R22 test and are within the tolerances as stipulated by the code.

Compared with a R22 test, the mechanical test speed with the high molecular test gas R134a will be some 15 percent lower. The fundamental requirement for a valid performance test, namely similar flow coefficients at the inlet to the individual stages is also fulfilled, as can be noted on Table 7. With the exception of the last stage, the deviations of the flow factors design/test are smaller than 1.5 percent.

The calculated performance curves (Figures 2 and 3) reveal close similarity over the full range. At the LP-section, the calculated R134a characteristic follows the shape of the design propane closer than the R22 characteristic. Compared with the basic propane curve, it is slightly shifted by 0.3 percent towards smaller volume flow. A similar coincidence can be noted at the HP-section; compared to the propane curve, both the R22 and R134a characteristics are flatter at higher than design flow and indicate a 1.0 to 1.5 percent larger throughput.

RESULTS OF A CLOSED LOOP PERFORMANCE TEST

One of the compressor manufacturers (ICAAMC member) carried out a performance test on an eight-stage wet gas compressor using R22 and R134a for comparative purposes. For both tests, the same closed loop system and the identical instrumentation were used. The test arrangement is shown in Figure 4. Throttle valves between discharge of first and inlet of second stage group, respectively, between discharge of second and inlet of first stage group and two flow meters facilitated measuring the speed lines from 115 percent design flow to surge.

The evaluation is based upon the following published equations of state:

Freon R22—Refrigerant Equations No. 2313, du Pont de Nemours

R134a—Thermodynamic Properties of R134a, (July 1992) National Institute of Standards and Technology (N.I.S.T.), Boulder, Colorado, USA

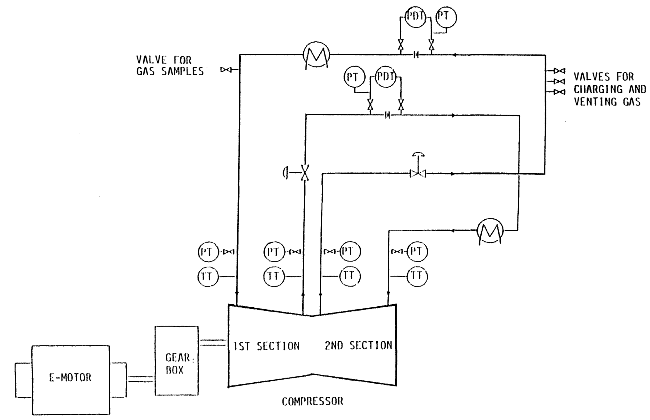

Figure 4. Test Setup for Closed Loop Performance Test.

The evaluated test curves of polytropic head coefficient and relative polytropic efficiency *vs* flow coefficient for both stage groups are presented in Figures 5 and 6. The test data for the various test points are listed numerically in Table 8.

Table 8. Results of Performance Tests with FREON 22 and R134a.

Test gas Used Equation		FREON 22 "DUPONT DENEMOURS"			R134a "N.I.S.T."	
		Section -1-			*Section -1-*	
Measuring Point	Volume Coeff.	Polytr. Head Coeff.	Relative Pol. Eff.	Volume Coeff.	Polytr. Head Coeff.	Relative Pol. Eff.
1	0.0893	1.7752	0.958	0.08763	1.79651	0.951
2	0.0864	1.8552	0.971	0.08301	1.95301	0.971
3	0.0838	1.9395	0.981	0.08414	1.94761	0.971
4	0.0699	2.2156	0.993	0.08393	1.94908	0.978
5	0.0539	2.2675	0.931	0.06898	2.22195	0.972
6				0.06831	2.22326	0.983
7				0.05361	2.26853	0.915
		Section -2-			*Section -2-*	
1	0.023	0.8876	0.669	0.02327	0.90045	0.679
2	0.0221	1.30209	0.866	0.01994	1.68376	0.986
3	0.0201	1.66744	0.975	0.02011	1.67957	0.985
4	0.0174	1.89235	0.983	0.02019	1.67317	0.926
5	0.0136	1.98166	0.92	0.01683	1.92274	0.993
6				0.01675	1.92167	0.987
7				0.01276	1.98596	0.919

The deviations in head and in efficiency of the recorded sets of test points are well within the measuring tolerances (Table 9). The listings in Table 10 and 11 also confirm that the conditions, with respect to circumferential Mach number and Reynolds number, are very similar for both test gases. Generally, it can be stated that the results of the two tests are compatible and are fully acceptable.

CONCLUSIONS

Comparable performance calculations with R22 and R134a and, appreciating the good agreement of the performance tests of a hydrocarbon gas compressor carried out with these two gases, lead to the conclusion that R134a is an acceptable substitute gas for closed loop performance testing. Whether the accuracy of the test evaluation (and eventually the conversion to specified process conditions) can be kept within the tolerances as required by the compressor test codes very much depends upon the gas equations of state employed.

Several companies which market R134a refrigerant gas and institutes of Universities have developed equations of state. There

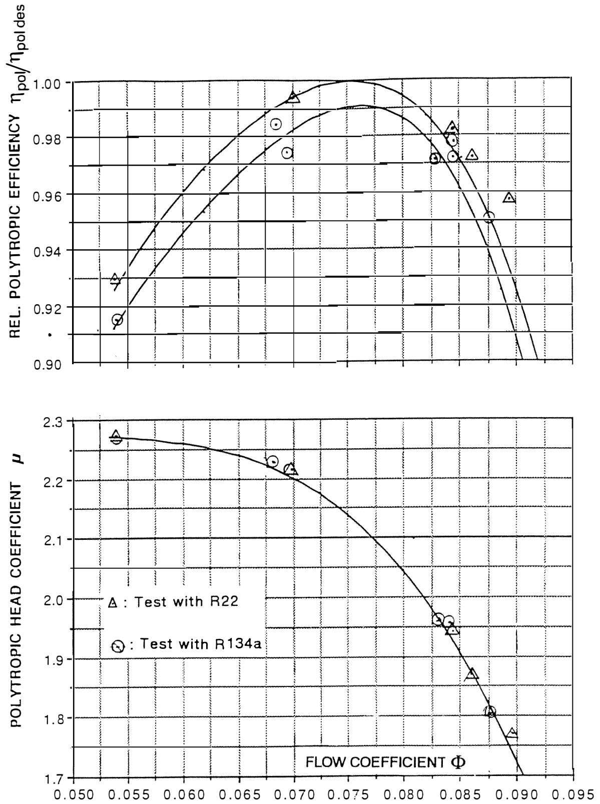

Figure 5. Performance Curves of Closed Loop Test. LP-section.

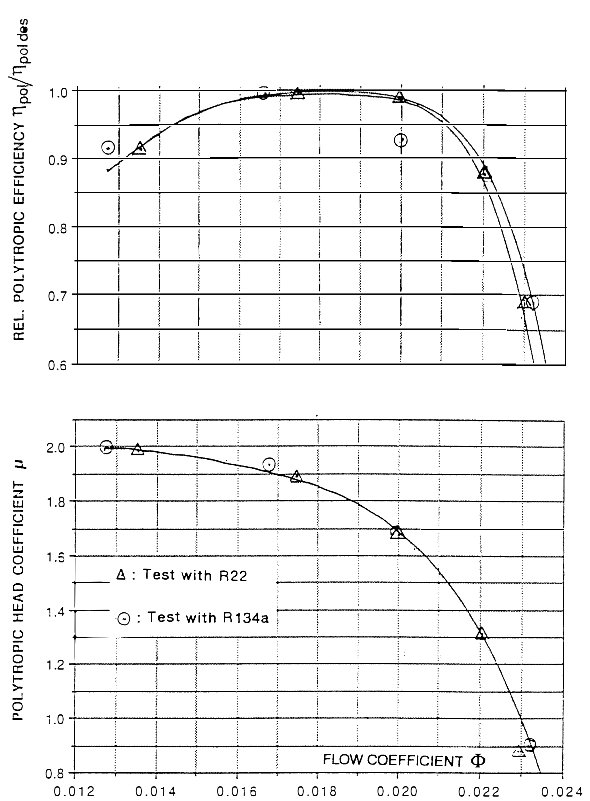

Figure 6. Performance Curves of Closed Loop Test. HP-section.

Table 9. Comparison of Performance Tests with FREON 22 and R134a.

	Section -1-				*Section -2-*					
Test Gas Used	FREON 22		R134a		FREON 22		R134a		Measuring Tolerances	
Equation	"DUPONT"		"N.I.S.T."		"DUPONT"		"N.I.S.T."			
	Head %	Effi. %	Head %	Effi. %	Head %	Eff. %	Head %	Eff. %	Head %	Effi. %
Design Flow	ref.	ref.	-0.1	-1.3	ref.	ref.	0.1	0.4		
Surge Flow	ref.	ref.	0	-1	ref.	ref.	0	0	1.1	1.7
115% Des. Flow	ref.	ref.	-0.9	-0.4	ref.	ref.	0	0.6		
Av. Values	ref.	ref.	-0.3	-.09	ref.	ref.	0	0.3		

Table 10. Comparison of Mach Numbers and Reynolds Numbers between the Test Gases FREON 22 and R134a LP-Section.

	Circumfer. Mach No. Mu2		*Reynolds No. * 10 E 6*	
Measuring Point	FREON 22	R134a	Freon 22	R134a
1	0.796	0.766	2.04	2.07
2	0.787	0.764	1.91	2.09
3	0.785	0.775	1.83	2.09
4	0.783	0.772	2.14	2.05
5	0.778	0.765	2.27	2.17
6		0.759		2.13
7		0.761		2.22
Average Value	0.786	0.766	2.04	2.12
	Ratio: 0.766/0.786 = 0.975		Ratio: 2.12/2.04 = 1.04	

exists no known competent comparison between the various published algorithms; but since these equations consider measurements along with published test data, the deviations most likely are very small.

The chosen NIST equation of state for the evaluation of the R134 test relies on a very extensive survey of published test data and incorporates the most recent experimental work to determine the coefficients for representing the thermodynamic surface.

The equation is an especially developed 32 constant modified MBWR equation. The MBWR coefficients were obtained via a multiproperty fit, using experimental data for PVT properties, isochoric heat capacity, second virial coefficients, speed of sound, and coexistence properties.

The equation is applicable to both the liquid and vapor phase up to 70 MPa and for a temperature range from the triple point to 450 K. The accuracy of the equation of state is based on comparisons with experimental data and amounts to:

Table 11. Comparison of Mach Numbers and Reynolds Numbers between the Test Gases FREON 22 and R134a HP-Section.

	Circumfer. Mach No. Mu2		*Reynolds No. * 10 E 6*	
Measuring Point	FREON 22	R134a	Freon 22	R134a
1	0.774	0.756	0.984	0.961
2	0.774	0.748	1.48	0.901
3	0.774	0.759	1.51	0.913
4	0.776	0.777	1.34	0.972
5	0.774	0.751	1.28	0.836
6		0.749		0.834
7		0.751		0.821
Average Value	0.774	0.756	1.32	0.891
	Ratio: 0.765/0.774 = 0.976		Ratio: 0.891/1.32 = 0.675	

Density = + 0.2 percent
Specific heat value at constant. volume = + 1.0 percent
Velocity of sound = + 0.6 percent (except critical region)

RECOMMENDATIONS

The ICAAMC working group has identified R134a as a suitable substitute gas for R22, and therefore recommends banning of R22 (and other gases containing chlorine) as a closed loop test gas as soon as possible, but not later than by the end of 1993. The working group further recognizes that the thermodynamic properties of R134a as published by the National Institute of Standards Technology (July 1992) are appropriate for the performance evaluation.

NOMENCLATURE

a_1	(m/s)	Sonic speed at impeller inlet = $\sqrt{T_1 R z_1 k}$
D_2	(m)	Impeller tip diameter
h_{eff}	(J/Kg)	Effective head
h_{pol}	(J/Kg)	Polytropic head
k	(-)	Isentropic exponent
M_{u2}	(-)	Circumferential (machine) Mach number
R	(J/Kg °K)	Gas constant
T	(°K)	Temperature
u_2	(m/s)	Impeller tip velocity
V_1	(m^3/s)	Suction volume flow
z_1	(-)	Compressibility factor
Φ	(-)	Flow coefficient $\frac{V_1}{D_2^2 u_2}$
μ_{pol}	(-)	Polytropic head coefficient
η_{pol}	(-)	Polytropic efficiency

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